

Support for a prosaic explanation for the anomalous acceleration of Pioneer 10 and 11

Louis K. Scheffer*
 Cadence Design Systems
 555 River Oaks Parkway
 San Jose, CA 95134
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Anderson, *et al.* find the measured trajectories of Pioneer 10 and 11 spacecraft deviate from the trajectories computed from known forces acting on them. This unmodelled acceleration can be accounted for by non-isotropic radiation of spacecraft heat. This explanation was first proposed by Murphy, but Anderson, *et al.* felt it could not explain the observed effect. This paper includes new calculations on the expected magnitude of this effect, based on the relative emissivities of the different sides of the spacecraft, as estimated from the known spacecraft construction. The calculations indicate the proposed effect can account for most, if not all, of the unmodelled acceleration.

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I. INTRODUCTION

In [1], Anderson *et al.* compare the measured trajectory of spacecraft against the theoretical trajectory computed from known forces acting on the spacecraft. They find a small but significant discrepancy, referred to as the unmodelled or anomalous acceleration. It has an approximate magnitude of $8 \times 10^{-8} \text{ cm s}^{-2}$ directed approximately towards the Sun. Needless to say, *any* acceleration of *any* object that cannot be explained by conventional physics is of considerable interest, and these spacecraft have been tracked very accurately over a period of many years, so the data is quite reliable. Explanations for the acceleration fall into two general categories - either new physics is needed or some conventional force has been overlooked.

In [2], Murphy proposes that the source of the acceleration is non-isotropic radiation from the main spacecraft bus. In [3] and [4], Anderson *et al.* reply with reasons that lead them to believe the proposed mechanism is not correct. Their main argument is that the cooling louvers are known to be closed, as opposed to open louvers assumed by Murphy. This, they felt, would result in isotropic radiation of heat.

This paper argues that non-isotropic radiation is in fact the most likely cause for the unmodelled acceleration, and the objections to it are overstated. Put most simply, all the heat dissipated in the body of the spacecraft must eventually be radiated by some externally visible surface. Assuming a uniform internal temperature, the power emitted from each surface is proportional to the area times the effective emissivity of the surface. Using the known construction and temperatures of Pioneer 10/11, we conclude most of the heat will be radiated from the anti-sunward faces of the spacecraft, even though the louvers are closed. Rough numerical calculations indicate this effect accounts for much, if not all, of the anomalous

acceleration.

II. PREVIOUS WORK

For the convenience of the reader, section 2.1 consists of direct quotes from [4], covering the relevant details of the Pioneer spacecraft. The references cited in this section are included in the references of this paper. Many other web and paper descriptions are available [5, 6].

In section 2.2 we summarize the existing literature on the hypothesis that non-isotropic radiation from the main spacecraft bus is responsible for the unmodelled acceleration.

A. General description of the Pioneer spacecraft, from [4]

The main equipment compartment is 36 cm deep. The hexagonal flat top and bottom have 71 cm long sides. The equipment compartment provides a thermally controlled environment for scientific instruments.

The majority of the spacecraft electrical assemblies are located in the central hexagonal portion of the compartment, surrounding a 16.5-inch-diameter spherical hydrazine tank. Most of the scientific instruments' electronic units and internally-mounted sensors are in an instrument bay ("squashed" hexagon) mounted on one side of the central hexagon. The equipment compartment is contained within a structure of aluminum honeycomb which provides support and meteoroid protection. It is covered with insulation which, together with louvers under the mounting platform, provides passive thermal control.

The spacecraft instrument compartment is thermally controlled between approximately 0 F and 90 F. This is done with the aid of thermo-responsive louvers located at the bottom of the equipment compartment. These louvers are adjusted by bi-metallic springs. They are completely closed below ~ 40 F and completely open

*Electronic address: lou@cadence.com

above ~ 85 F. This allows controlled heat to escape in the equipment compartment. Equipment is kept within an operational range of temperatures by multi-layered blankets of insulating aluminum plastic. Heat is provided by electric heaters, the heat from the instruments themselves, and by twelve one-watt radioisotope heaters powered directly by non-fissionable plutonium

The essential platform temperature as of the year 2000 is still within acceptable limits at -41 F; the nominal range is between -63 F and 180 F. The RF power output from the TWT-A traveling-wave-tube amplifier is still within normal parameters, having a value of 36 dBm[7]. (The nominal range is 27 to 40 dBm.)

The spacecraft needs 100 W to power all systems, including 26 W for the science instruments. Previously, when the available electrical power was greater than 100 W, the excess power was either thermally radiated into space by a shunt-resistor radiator or it was used to charge a battery in the equipment compartment.

At present only about 65 W of power is available to Pioneer 10 [8]. Therefore, all the instruments are no longer able to operate simultaneously. But the power subsystem continues to provide sufficient power to support the current spacecraft load: transmitter, receiver, command and data handling, and the Geiger Tube Telescope (GTT) science instrument.

B. Non-isotropic radiative cooling of the spacecraft

Murphy suggests that the anomalous acceleration seen in the Pioneer 10/11 spacecraft can be, “explained, at least in part, by non-isotropic radiative cooling of the spacecraft.” [2] Anderson, *et al.* argue in reply that this explanation is flawed, since “by nine AU the actuator spring temperature had already reached ~ 40 F [5]. This means the louver doors were closed (i.e., the louver angle was zero) from where we obtained our data. Thus, from that time on of the radiation properties, the contribution of the thermal radiation to the Pioneer anomalous acceleration should be small.” They also argue that the spacecraft power is decreasing, but the unmodelled acceleration is not.

III. DISCUSSION

The sunward side of the spacecraft is the back, and the anti-sunward side, in the direction of motion, is the front[9]. We consider thermal radiation from the spacecraft with the louvers closed, as they have been since 9 AU. We consider the radiation from the front, back, and sides of the spacecraft bus. Assuming the compartment is at a constant temperature, the radiation from each surface will be determined by the effective emissivity of that surface times its area.

First, from the known sizes the front and back of the central equipment compartment have about 1.3 m^2 area,

and the sides about 1.5 m^2 total. The sides (and presumably the rear) of the compartment are covered with multi-layer insulation. From [10], multilayer insulation from spacecraft typically has an effective emissivity of 0.002 to 0.02. Assuming a value of 0.01, and an internal temperature of 233 K, the instrument compartment will lose about 5 watts through the sides and back. Ignoring conduction losses through connecting wires and struts, then the rest of the power (about 59 watts as of 1998) must be radiated from the front.

Is it reasonable for the front to radiate this much? At 233 K, the area times the emissivity must equal 0.35 m^2 . If the surface was flat, this would require an average emissivity of 0.27. From a picture of the Pioneer 10 replica in the National Air and Space Museum [11], the front of the spacecraft is rather complex, with supports, louvers, and a variety of surface finishes. A composite emissivity of 0.27 seems reasonable.

The main conclusion seems quite robust. Multi-layer insulation is specifically designed to reduce heat losses, whereas the louvers have at most one layer of obstruction even when closed. (The Rosetta louvers, for example, have an emissivity range of 0.09-0.76[12].) Therefore a majority of the heat will be radiated from the front of the spacecraft.

A. Radio beam power

The radio beam power is reported in [4] two different ways, as 8 watts and 36 dBm. These values are not consistent, since $36 \text{ dBm} \sim 3.98 \text{ watts}$. Assuming the dBm figure is correct, the smaller value of radiated power reduces the value of the anomalous acceleration.

B. Effect on the unmodelled acceleration

Anderson reports an unmodelled acceleration for Pioneer 10 of $7.84 \times 10^{-8} \text{ cm/sec}^2$. If the radio beam is 4 watts instead of 8, this becomes $7.31 \times 10^{-8} \text{ cm/sec}^2$. As of 1998, the power in the main bus was about 68 watts. If 4 watts goes into the radio beam, and 5 watts through the sides of the instrument compartment, then 59 watts must radiate from the front. If this radiated as if from a flat plate[2], then this accounts for $5.2 \times 10^{-8} \text{ cm/sec}^2$. If it is radiated as a collimated beam, then the resulting acceleration is $7.8 \times 10^{-8} \text{ cm/sec}^2$. The true result should lie somewhere between these two extremes.

This explanation also explains some other puzzles: the values of acceleration of Pioneer 10 and 11 would be expected to be similar, but not identical, as observed. The acceleration would not have a strong effect on the spin; since the louvers are closed, the radiation will generate little torque. Other spacecraft, built along the same general principles, would be expected to show a similar effect, but planets and other large bodies would not, as is observed.

C. Why is the acceleration not dropping as the power level drops?

This is covered in more detail by Murphy[2]. As the total power level drops, some parts of the spacecraft will dissipate less power (such as the shunt regulators and science instruments) and some will remain the same (command and control, and the transmitter, for example). If the hypothesis put forth in this paper is true, then the acceleration of the spacecraft should be proportional to the power dissipated in the central equipment compartment. The construction of the spacecraft puts most of the experiments on the outside and most of the house-keeping functions in the central compartment. Since the central compartment contains mostly systems essential to the operation of the spacecraft, the power dissipated within it has changed comparatively little. This explains why the unmodelled acceleration has changed little despite the considerable reduction in spacecraft power.

IV. CONCLUSIONS AND FUTURE WORKS

There is surely an unmodelled effect on the Pioneer spacecraft, based only on its thermal characteristics. Rough estimates show it may account for most, if not

all, of the unmodelled acceleration.

More detailed modeling, using the Pioneer materials, construction details, and history, could provide a much better estimate of the magnitude of this effect. A suitably detailed thermal model, measured in a cold vacuum chamber, would provide the strongest evidence for or against this hypothesis.

Proposed missions such as LISA[13] will attempt to detect gravitational waves by measuring the changes in distance between spacecraft about 5×10^9 meters apart with an accuracy of a few picometers. They will then look for unmodelled displacement. To find the anticipated small effects, the LISA project isolates the spacecraft from non-gravitational disturbances by actively controlling them to keep them centered around a “drag-free” proof mass. This technique should keep the acceleration induced by non-gravitational forces to about 10^{-13} cm/sec², or about 1 part in 10^5 of the proposed anomalous acceleration. Given this accuracy, and the proposed formation of a triangle inclined to the ecliptic, an anomalous acceleration as proposed for Pioneer 10/11 will be easily distinguishable from the conventional gravitational forces. If no anomalous accelerations are detected in this more precise experiment, then almost surely the unmodelled acceleration of Pioneer 10 and 11 is caused by some overlooked prosaic source such as the one proposed here.

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 - [5] *Pioneer F/G Project: Operational Characteristics*, Pioneer Project NASA/ARC document No. PC-202 (NASA, Washington, D.C., 1970).
 - [6] For web summaries of Pioneer, go to:
<http://quest.arc.nasa.gov/pioneer10>,
<http://spaceprojects.arc.nasa.gov/SpaceProjects/pioneer/PNhome.html>
 - [7] dBm is used by radio engineers as a measure of received power. It stands for decibels referred to a milliwatt. [Note: the articles by Anderson define it as power below a milliwatt, which is inconsistent with the sign of their usage.]
 - [8] This is a “theoretical value,” which does not account for inverter losses, line losses, and such. It is interesting to note that at mission acceptance, the total “theoretical” power was 175 Watts.
 - [9] When a Pioneer antenna points toward the Earth, this defines the “rear” direction on the spacecraft. The equipment compartment placed on the other side of the antenna defines the “front” direction on the spacecraft.
 - [10] http://www.frc.ri.cmu.edu/projects/lri/Luna/report/therm_chap.html#HDR12
 - [11] <http://www.nasm.edu/galleries/gal100/pioneer.html>
 - [12] www.estec.esa.nl/spdwww/rosetta/cdr/docs/datapack/ro-mmb-ds-3101i5.pdf
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